Twenty-Sixth Symposium (International) on Combustion/The Combustion Institute, 1996/pp. 1541–1547

THE TRANSPORT OF CARBON MONOXIDE FROM A BURNING COMPARTMENT LOCATED ON THE SIDE OF A HALLWAY

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An experimental study was conducted to investigate the transport of high concentrations of carbon monoxide (CO) from a burning compartment located on the side of a hallway. Opening sizes of 0.04 and 0.12 m^2 were used to vary the ability of the jet of fire products entering the hallway to entrain surrounding gases. By controlling the depth of the upper layer of oxygen-deficient combustion gases accumulated in the hallway during preflashover, the oxygen concentration of the gases entrained into the jet of fire products entering the hallway was varied. An increase in the upper-layer depth resulted in higher CO and UHC yields and lower CO_2 yields. When the depth of the layer fell below the bottom of the opening, downstream CO yields were found to increase to levels equivalent to or greater than yields measured inside the compartment, with the highest yields measured in experiments with external burning. Using the external burning as a flow visualization tool, the gases were observed to be transported nonuniformly down the hallway when the burning compartment was on the side. The bulk flow of the gases was to cross the hallway and then flow down the side of the hallway opposite the compartment. This nonuniformity in gas transport within the hallway was also evident in spatial and temporal measurements of species concentrations and temperature. In the hallway, during the postflashover period of the compartment fire, concentrations of CO greater than 2.0% were measured at locations along the wall opposite the compartment, while CO concentrations of only 0.8% were measured on the compartment side of the hallway. The data presented provides the first explanation for the tragic results of fires in health care facilities where CO inhalation was responsible for numerous deaths, and points to the necessary directions for reliable predictive tools.

Introduction

The total number of civilian deaths in home fires throughout the United States during 1994 dropped to an all time low of 3425 people [1]. The cause of death in building fires continues to be dominated by smoke inhalation (carbon monoxide poisoning), which accounted for 76% of the deaths in building fires during 1990, rising 1% every year from 1980 to 1990 [2].

Two-thirds of the carbon monoxide (CO) poisoning victims are typically found at locations distant from the room of fire origin [3]. One tragic example of this statistic occurred on October 5, 1991 at the Hillhaven Nursing Home in Norfolk, Virginia [4]. Twenty-three patients resided along the hallway that contained the burning room. Ten patients died in the fire, all from CO poisoning. Nine victims were in rooms on the side of the hallway opposite the burning room while only one victim was located on the burning room side of the hallway.

There have been numerous studies that have verified that high concentrations of CO (up to 4.5% in some full-scale experiments) exist at locations remote from the burning room [5–7], with some speculation on mechanisms responsible for the transport of high levels of CO [5]. In order to prevent people from perishing in fires such as the one mentioned, a thorough understanding of how CO is transported in lethal concentrations is essential. As part of a larger effort, an experimental study was performed to investigate both the conditions that enable fatally high concentrations of CO to be transported to remote locations, and the evolution of CO during its movement to areas distant from the burning room.

Experimental Methodology

The experiments were conducted with the burning room located on the side of the hallway to simulate an orientation commonly found in office

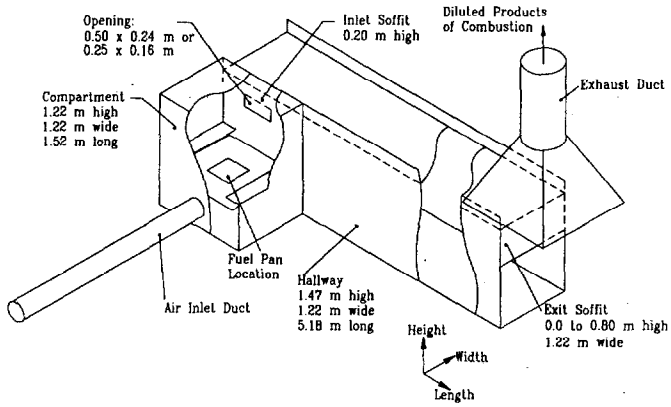

FIG. 1. The one-eighth-scale (by volume) experimental building fire facility at VPI&SU.

buildings and health care facilities (see Fig. 1). A detailed description of the one-eighth-scale (by volume) facility is given elsewhere [8]. Liquid hexane pool fires were burned in a 0.20 m circular fuel pan located in the middle of the room. The compartment global equivalence ratio (defined as the ratio of the fuel vaporization rate and the air entrainment rate into the compartment divided by the stoichiometric fuel to air ratio) was approximately 3.0 ± 0.3 during the postflashover period of the compartment in all the experiments. Exhaust duct sampling was performed to investigate the overall oxidation of the gases in the hallway, while in-hallway and in-compartment sampling were performed to understand the evolution of the fire gases in the hallway.

The fluid mechanics and the thermochemical environment at the location where the fire product gases enter the hallway can significantly affect the level of CO transported to areas where CO oxidation reactions are frozen (termed remote locations). The fluid mechanics of the compartment exhaust gases can be altered by varying the inlet soffit height (the distance between the top of the opening and the ceiling) and the size of the opening [9]. All experiments were performed with a 0.20-m-inlet soffit, while a 0.12 m^2 (0.50 m wide, 0.24 m high) and a 0.04 m^2 (0.25 m wide, 0.16 m high) opening size were utilized in the study. The thermochemical environment at the hallway entrance was altered by varying the depth of combustion gases in the hallway (termed the upper-layer depth). The upper-layer depth was increased by gradually blocking off the upper portion of the hallway exit in 0.10 m increments (termed the hallway exit soffit) and varied from 0.0 m to 0.80 m. Experiments were also performed with the bottom 1.27 m of the hallway exit blocked, leaving a 1.22 m wide, 0.20 m high opening for the gases to escape the hallway.

Results and Discussion

Effect of Hallway Upper-Layer Depth Variation

The upper-layer depth in the hallway determines the thermochemical environment into which the compartment fire products exhaust. The depth was experimentally controlled by the exit soffit height which remained fixed during an experiment. The upper-layer depth was visually observed to be approximately equivalent to the exit soffit height except for experiments with an exit soffit equal to or less than 0.20 m. In the cases with exit soffits of 0.0, 0.10, and 0.20 m, the upper-layer depth was determined to be equivalent to 0.20 m in all three instances, using temperature profiles. The effect of varying the thermochemical environment on the downstream combustion product yields is investigated for different opening sizes.

The species yields, $Y_i = \dot{m}_i/\dot{m}_{vap}$, downstream of the hallway were determined from the known mass flow rate of species i ($\dot{m}_i$) in the exhaust duct, and the fuel vaporization rate, $\dot{m}_{vap}$, of the pool fire. The yields of CO, unburned hydrocarbons (UHCs), and CO_2 are plotted versus a nondimensional upper-layer depth, $\gamma = \delta/z$, which is defined as the upper-layer depth divided by the distance between the ceiling and the bottom of the opening connecting the compartment and the hallway (z = 0.44 m with a 0.12 m^2 opening, and z = 0.36 m with a 0.04 m^2 opening). Physically, γ represents the degree to which the plume of compartment fire gases entering the hallway is surrounded by oxygen-deficient combustion gases. The value of z in cases where a door is present instead of an opening is the distance between the neutral plane and the ceiling. The results of varying γ in experiments with an opening size of 0.12 and 0.04 m^2 are shown in Figs. 2 and 3, respectively. Each data point shown in both figures was generated by averaging 60 s of data during the compartment postflashover period.

With the upper-layer depth no greater than the inlet soffit height (γ = 0.45 with a 0.12 m^2 opening, and γ = 0.55 with a 0.04 m^2 opening), the species yields are relatively constant. The average yield of 0.098 for CO and 0.046 for UHCs are the lowest measured yields for a 0.12 m^2 opening, while the CO_2 is at its highest level of 2.58 (see Fig. 2). The

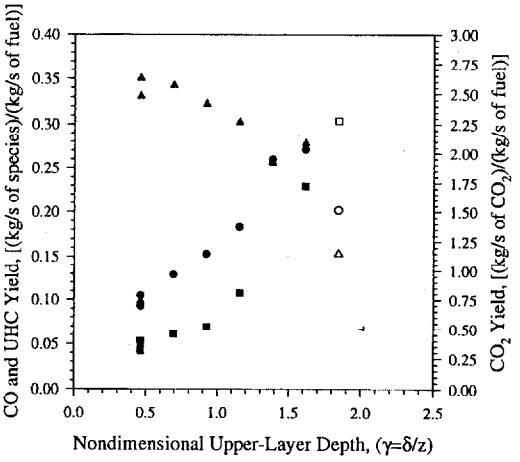

FIG. 2. The CO (●), UHC (■), and CO_2 (▲) yield in the exhaust duct downstream of the hallway for experiments with $\phi = 3.0$ and an opening size of 0.12 m^2. Open symbols are experiments with no external burning.

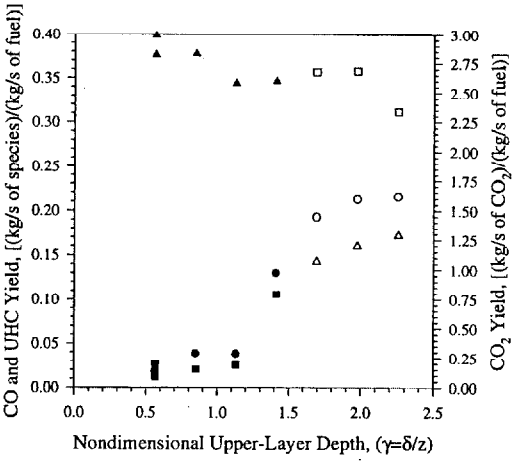

FIG. 3. The CO (●), UHC (■), and CO_2 (▲) yield in the exhaust duct downstream of the hallway for experiments with $\phi = 3.0$ and an opening size of 0.04 m^2. Open symbols are experiments with no external burning.

same trend was observed with the 0.04 m^2 opening, with minimum average CO and UHC yields of 0.018 and 0.019, respectively, and a maximum average CO_2 of 2.94. The less complete oxidation of the compartment fire gases in the 0.12 m^2 opening experiments, evident through the higher CO (by 0.08) and UHC yields (by 0.027) in addition to the lower CO_2 yields (by 0.36), was attributed to the less effective air entrainment into the buoyant jet of compartment fire gases in this case.

As the hallway upper-layer depth begins to fall below the top of the opening such that it surrounds the sides of the jet exiting the compartment, the jet entrains more oxygen-deficient combustion gases, limiting the oxygen entrainment into the compartment fire gases. An increase in the upper-layer depth results in less complete combustion of the compartment fire gases, causing a gradual increase in the CO and UHC yields and decrease in CO_2 yield (Figs. 2 and 3). The entrainment of less O_2 into the jet reduces the pool of radicals (H, HO_2, OH, O, HCO, etc.) necessary for the oxidation of CO and UHCs. The rapid generation of radicals is critical to the oxidation of CO because CO will not begin to oxidize until the UHC concentrations have been reduced to levels where the CO oxidation reactions are competitive with the UHC oxidation reactions [9]. If the generation of radicals is inhibited, less CO will be oxidized before the gas temperature falls below 850 K, where CO oxidation rate decreases drastically [10–12]. The gradual increase in CO and UHC yields continues until $\gamma \geq 1.4$ (Figs. 2 and 3).

When the hallway upper-layer depth increases to levels where $\gamma \geq 1.4$, the species yields were measured to be less dependent on the upper-layer depth and more dependent on the presence or absence of external burning in the hallway. With external burning occurring in the hallway and $\gamma \geq 1.4$, the yield of CO downstream of the hallway is seen in Fig. 3 to be 0.27 (on average) which is approximately 23% higher than levels measured inside the compartment (on average 0.22 for $\phi > 1.8$). The UHC yields in these experiments were, however, approximately 27% lower than the levels inside the compartment (on average 0.33 $\phi > 1.8$), with downstream yields measured to be 0.24 on average. The limited radical pool generated in the oxygen-deficient environment surrounding the jet was, therefore, utilized to oxidize mostly UHCs, which forms additional CO. If the upper-layer depth is increased to levels where $\gamma > 1.7$, the jet of compartment fire gases issues into a hallway upper-layer environment where oxygen deficient levels are low enough to inhibit the ignition of the flammable combustion gases. The yields of CO, UHCs, and CO_2 were all measured to be equivalent in magnitude to levels measured inside the compartment (Figs. 2 and 3).

In comparing downstream species yields from experiments with the same hallway global equivalence ratio (e.g., the same exit soffit height and the same amount of fuel entering the hallway), the CO and UHC yields in experiments with a 0.04 m^2 opening are seen in Fig. 3 to be lower compared to the yields seen in Fig. 2 with a 0.12 m^2 opening and $\gamma < 1.4$. With difference in the yields attributed to the more efficient entrainment of oxygen in the 0.04 m^2 case, the downstream species yields depend on the plume equivalence ratio of the gases entering the hallway.

Flow Visualization

With the compartment-hallway orientation shown in Fig. 1, the flow field in the hallway is highly three-

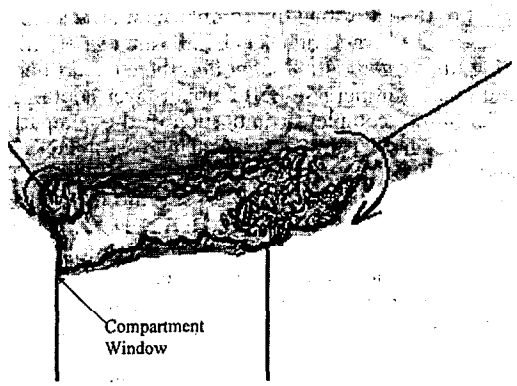

FIG. 4. An image of the external burning in the hallway, with a 0.10 m exit soffit, revealing how the combustion gases are transported away from the compartment.

dimensional. Since laboratory techniques for measuring the flow field in the hallway are not practical for the reported experiments, the flame emissions in the hallway (external burning) were used to reveal how the gases were transported away from the compartment and down the hallway. The path of the combustion gases can most easily be visualized when the gases exiting the compartment encounter concentrations of oxygen near those observed in the ambient surroundings (i.e., experiments with an exit soffit of 0.10 m or less). The visualization was performed with a video camera viewing the fire from the hallway exit with the following description given from this perspective.

An image of the external burning, with a 0.10 m exit soffit which is typical during the postflashover period of the compartment fire, is shown in Fig. 4. As the combustion gases exit the compartment, the 0.20 m inlet soffit allows a buoyant plume to be formed at the hallway entrance. The majority of the external burning is observed to be present both across and along the upper right corner of the hallway (Fig. 4). Based on this observation, the bulk of the combustion gases are driven across the hallway by the momentum of the jet exiting the compartment. The bulk flow of combustion gases then impinges upon the opposite wall, causing a large, clockwise-rotating vortex to develop in the upper right corner of the hallway (Fig. 4).

Species Concentration Evolution in the Hallway

To investigate the spatial and temporal evolution of species concentrations in cases where high levels of CO are being transported to remote locations, a series of 25 experiments was performed with a 0.12 m^2 opening and a 0.61 m exit soffit (γ = 1.4). This combination of opening size and exit soffit height was chosen in particular because of the particularly high levels of CO at remote locations despite the presence of external burning. Sampling was performed 0.05 m below the ceiling at a different location within the facility during each experiment, with the locations denoted by the letters in the plots to follow. The occurrence of flashover (the time at which a steep rise in the equivalence ratio occurred, $\phi \approx 1.5$) was used to align the 25 experiments, so time averaging was performed at approximately the same instance before and after flashover. The measured data at various spatial locations were time averaged over a 4 s period. The origin of the y-axis corresponds to the center of the opening. Within the narrative description to follow, two-dimensional plots of the wet concentrations of CO and UHCs are used to display both the movement of CO and the effects of external burning on CO and UHC levels in the hallway.

Carbon monoxide began to accumulate (0.1%) in the upper layer of the compartment as flashover was reached. Carbon monoxide in a concentration of greater than 1.0% was measured in the gases migrating across the hallway 24 s after flashover.

The nonuniform transport of the combustion gases down the hallway was observed in the CO concentration distribution 40 s after flashover (Fig. 5). Toxic levels of CO (2.0%) were measured on the side of the hallway opposite the compartment, while only 0.8% CO was present on the compartment side of the hallway. Assuming that a 50% carboxyhemoglobin (COHb) level in the bloodstream will cause death, CO levels of 2.0% CO and 0.8% result in death in 3 min and 10.5 min, respectively [13].

The rapid recirculation of combustion gases resulted in uniform species concentrations, including CO, within the hallway upper layer 68 s after flashover. At this time, the CO concentration was approximately 2.1% in the presence of approximately 3.5% UHC, 8.5% CO_2, and 3.5% O_2.

Despite the occurrence of external burning in the hallway approximately 80 s after flashover, the CO concentration in the hallway upper layer 96 s after flashover remained uniform at 2.1% (Fig. 6). The occurrence of external burning is evident, however, in the UHC concentration plot 96 seconds after flashover (Fig. 7). The external burning caused a low concentration area (1.0–1.5%) of UHCs to develop along the wall opposite the compartment (Fig. 7) where the gases were previously noted to travel after initially crossing the hallway. The external burning did not release a sufficient amount of heat to compensate for the heat losses, and the gas temperature cooled rapidly from approximately 950 K to less than 800 K by the time they traveled approximately 1.0 m along the opposite side of the hallway. These low temperatures prevented CO oxidation and allowed the CO, as is seen in Fig. 6, to be transported down the length of the hall in fatally high concentrations where gas temperatures were only 600 K. External

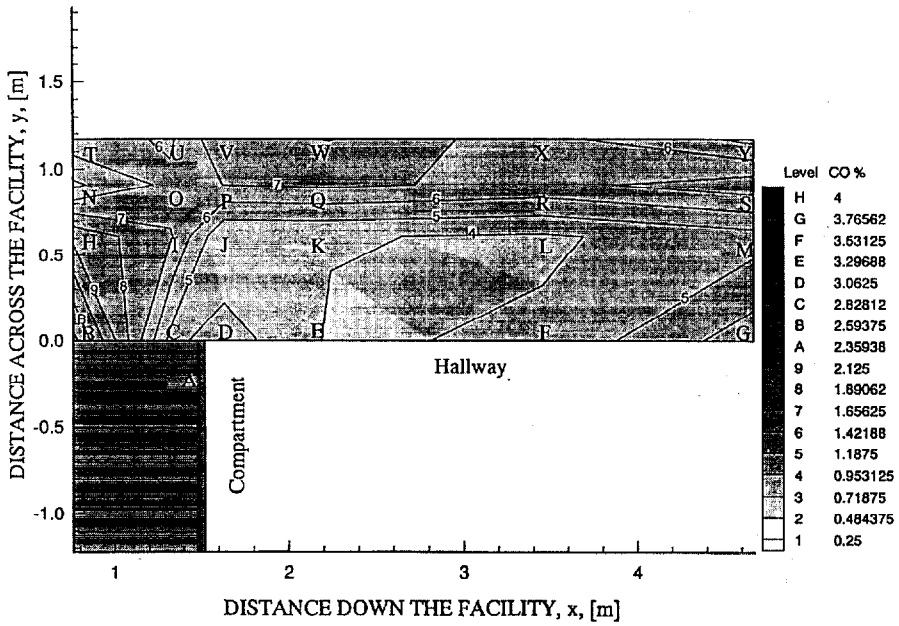

FIG. 5. The distribution of the CO concentration 0.05 m below the ceiling in the hallway during the 40 to 44 s time interval after flashover. Experiments run with a 0.12 m^2 opening and $\phi = 3.0$ during the postflashover stage of the fire.

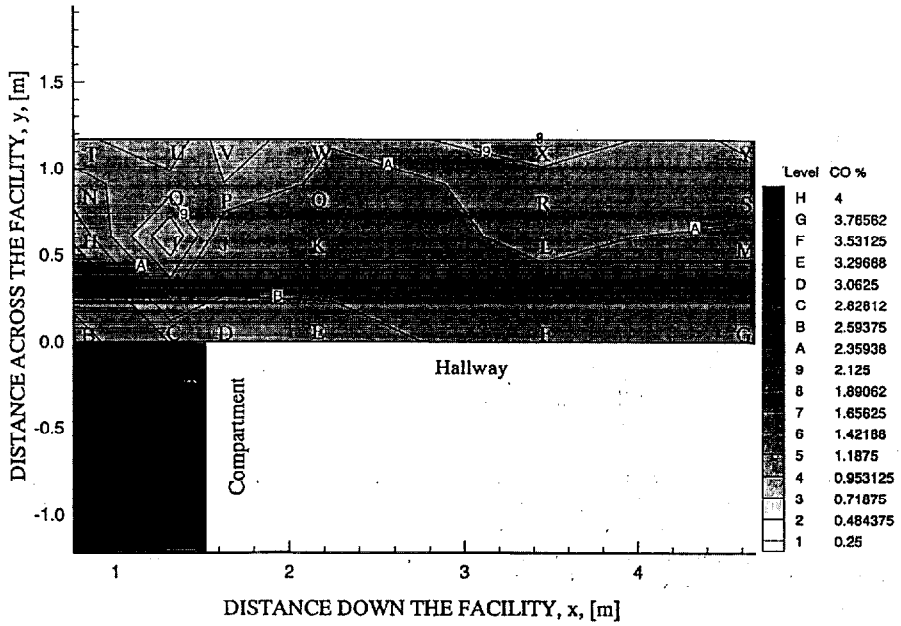

FIG. 6. The distribution of the CO concentration 0.05 m below the ceiling in the hallway during the 96 to 100 s time interval after flashover. Experiments run with a 0.12 m^2 opening and $\phi = 3.0$ during the postflashover stage of the fire.

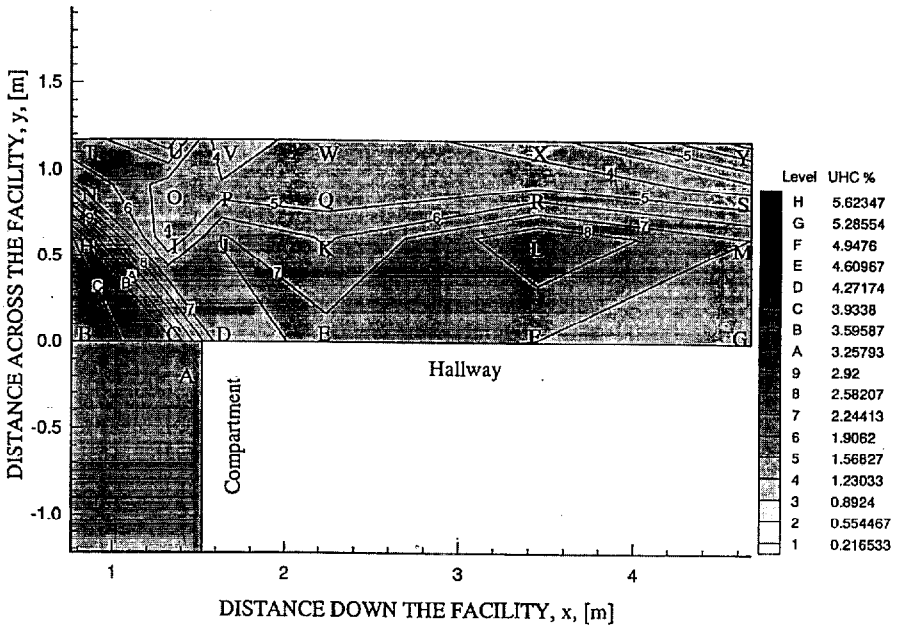

FIG. 7. The distribution of the UHC concentration 0.05 m below the ceiling in the hallway during the 96 to 100 s time interval after flashover. Experiments run with a 0.12 m^2 opening and $\phi = 3.0$ during the postflashover stage of the fire.

burning also resulted in nonuniform concentrations of O_2 and CO_2 with 1.0 and 10.0%, respectively, measured along the wall opposite the compartment and 3.5 and 8.5%, respectively, on the compartment side of the hallway.

Prior to the end of the experiment (approximately 140 s after flashover) with external burning still occurring, 10.5% CO_2 and 0.5% O_2 was uniformly distributed within the hallway. The UHCs were uniformly distributed within the hallway at a level of 1.0%, a reduction anticipated from the downstream yield data. The CO remained uniform in the hallway at 2.1%, a level that results in death after 2.8 minutes of exposure.

To investigate instances where a longer period of time was necessary for the species concentrations to become uniformly distributed within the hallway, experiments were conducted with the bottom portion of the hallway exit blocked, leaving a 0.20 m-high, 1.22 m-wide opening at the top of the hallway exit. The opening allowed some of the gases reaching the end of the hallway to exit while forcing the remainder of the gases to recirculate back toward the compartment. In experiments with a 0.04 m^2 opening, an upper-layer depth of approximately 0.40 m (γ = 1.11) was measured using temperature profiles. The nonuniformity in the CO levels within the hallway were measured to persist for nearly 95 s after flashover with 1.9% CO present in the gases along the side of the hallway opposite the compartment and 0.8% in the gases on the compartment side of the hallway. Even 130 s after flashover, the hallway remained slightly nonuniform with 2.0% on the side opposite the compartment and 1.5% on the compartment side.

Summary and Conclusions

The level of CO transported to remote locations is dependent on the air entrainment into the compartment fire gases entering the hallway, which is controlled in building fires by the depth of the upper layer of oxygen-deficient combustion gases, δ, in the space adjacent to the burning compartment. The nondimensional, upper-layer depth, $\gamma = \delta/z$ (where z is the distance between the ceiling and the bottom of the opening connecting the compartment and hallway) related the effect of the depth of the oxygen-deficient upper layer to the plume air entrainment. With $\gamma \geq 1.4$, the downstream CO yield was measured to be equivalent to or greater than levels measured inside the burning compartment. The downstream species yields were found to be related to the plume equivalence ratio of the compartment fire gases entering the hallway.

Through observing the external burning and examining the two-dimensional plots of hallway species concentrations, the gases exiting the compartment placed on the side of the hallway first convected across the hallway and then down the side of the hallway opposite the compartment.

The spatial and temporal evolution of species concentrations within the hallway was measured for an experiment with $\gamma = 1.4$ and external burning in the hallway. A gradient in the CO concentration across the hallway was observed to be present for approximately 68 s after flashover. Experiments simulating longer hallways required a longer period of time for species concentrations to become uniform. For the remainder of the postflashover period (approximately 80 s), a CO concentration of 2.1% was uniform within the hallway upper layer and was unaffected by the occurrence of external burning. As expected from the downstream yield data, a decrease in the UHC levels was measured with UHCs being depleted to concentrations of 1.0–1.5% by the time the gases had convected across the hallway.

The use of zonal models to predict overall yields at remote locations from the burning compartment works well when the postflashover time is much larger than the time necessary for the species concentrations in the upper layer to become uniform. In general, however, field models should be used to accurately predict the distribution of species concentrations in the hallway upper layer when the burning room is on the side of the hallway.

The data reported gives the first experimental explanation of the tragic consequences of fires similar to the Hillhaven nursing home fire [4]. The nonuniform transport of CO away from the burning room resulted in nine victims in rooms on the side of the hallway opposite the burning room while only one person died on the fire origin side of the hallway.

Acknowledgments

This work was supported by the U.S. Department of Commerce-NIST, the BFRL-Smoke Dynamics Research Group, and monitored by Dr. W. M. Pitts. Special thanks to Dr. C. L. Beyler and Dr. H. E. Nelson of Hughes Associates, Inc. for their input and suggestions regarding this research, and Mr. Jason Littleton for his aid in the experimental execution.

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